EXPERIMENTAL EVALUATION OF THE STRUCTURAL BEHAVIOUR OF ADOBE MASONRY STRUCTURAL ELEMENTS

H. Varum[1], A. Costa[2], H. Pereira[3], J. Almeida[4], H. Rodrigues[5], D. Silveira[6]

ABSTRACT

Rehabilitation and strengthening of existing adobe masonry constructions have been neglected during the last decades. In Aveiro, Portugal, many adobe buildings present an important level of structural damage and, in many cases, are even near to ruin, having the majority a high vulnerability to seismic actions. To face the lack of information concerning the mechanical properties and structural behaviour of adobe elements, it was developed an experimental campaign. The composition and mechanical behaviour of adobe units and mortars were studied. Laboratory and *in situ* tests on full-scale adobe masonry walls were performed. Adobe walls were subjected to imposed horizontal cyclic displacements. Test results reveal the behaviour and structural fragilities of adobe elements, and will help in the assessment of existing adobe constructions, and in the strengthening strategy definition.

1 Background

In the near past, earth was a very common construction material in Portugal. Adobe and rammed earth were used through years in almost all types of construction, having this utilization declined during the first half of 20th century, with the emergence of cement industry. Rammed earth was more applied in south and adobe in littoral center, especially in Aveiro district (Oliveira 1992, SAT 1992). Presently, according to information from the municipality, about 25% of the existing buildings in Aveiro city are made of adobe. It is estimated

[1]Auxiliar Professor, Dept. of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, hvarum@civil.ua.pt
[2]Full Professor, Dept. of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, acosta@civil.ua.pt
[3]Master student, Dept. of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, a21581@alunos.civil.ua.pt
[4]Research Assistant, Dept. of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, a20154@alunos.civil.ua.pt
[5]PhD student, Dept. of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, hrodrigues@aveiro-norte.ua.pt
[6]PhD student, Dept. of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, a25413@alunos.civil.ua.pt

that this percentage rises to 40% when referred to the entire district, reflecting the importance of this construction system in rural areas. Adobe can be found in varied types of construction: rural and urban buildings, many of which are still inhabited, walls for the delimitation of properties, water wells, churches and warehouses (Fig. 1). An important number of the urban adobe buildings are of cultural, historical and architectonic recognized value, namely of the "Art Nouveau" style. A more detailed description of the predominant constructive typologies can be found in Varum, Costa and Velosa (2006).

Adobe traditional constructions, if not properly designed and strengthened, may present a deficient response when subjected to cyclic actions, as those induced by earthquakes, suffering severe structural damage and frequently reaching collapse. Several recent earthquakes affecting earth building have evidenced the seismic vulnerability associated to this type of construction, when not properly strengthened. The El Salvador earthquakes of January and February, 2001 and the Bam, Iran, earthquake of December 26, 2003 are just two significant examples. In El Salvador earthquakes more than one million people were made homeless, having the majority of the damage occurred in adobe houses.

Portugal has been affected, in the last centuries, by several earthquakes of large and moderate intensity. Aveiro district is located in a region of moderate seismic hazard. However, due to the nature of the foundation soft soils, eventual earthquakes striking the region can be considerably amplified. The techniques adopted in the construction of adobe structures in Aveiro district were based in the accumulated experience, transmitted from generation to generation, and did not include a preoccupation with seismic safety. This constructed park is thus not properly reinforced to resist to seismic actions, suffering of various structural anomalies and deficiencies. The most frequent pathologies found in Aveiro adobe constructions are described in Varum, Costa and Velosa (2006).

Structural rehabilitation of the existing adobe constructions in Aveiro district is demanded, and constitutes an urgent matter. It presents, however, relevant difficulties, essentially due to the lack of information concerning properties and characteristics of the mechanical behaviour of adobe masonry. Technical studies for the determination of these properties and characteristics are thus necessary. The mechanical characterization of adobe existing masonry constitutes a fundamental instrument in the support of rehabilitation and strengthening projects, and even in the support of the design of new adobe constructions (Hernandez 2000).

Figure 1. Examples of existing adobe constructions in Aveiro district.

2 Experimental work developed

2.1 Introduction

A research group of the Civil Engineering Department, from the University of Aveiro, has been developing studies and experimental tests to aid filling the technical information gap concerning the structural behaviour of existing adobe constructions. Adobe units, taken from houses and land dividing walls, were characterized in terms of dimensions and granulometric composition. Cylindrical adobe specimens cores were subjected to compression and splitting tests, and prismatic mortar specimens were subjected to compression tests. The structural non-linear response of adobe walls has also been investigated in a series of full-scale tests, in the laboratory and *in situ*, with imposed horizontal cyclic displacements.

2.2 Granulometric characterization of adobe units

A basic composition characterization (granulometric analysis) of adobe samples taken from the constructions in study was carried out. The majority of the aggregates in the adobe units in study were classified as coarse sand. Samples with a larger proportion of fine particles were also found, but were less common.

2.3 Mechanical characterization of adobe units and mortars

2.3.1 Simple compression and splitting tests on adobe specimens

In Aveiro district, adobe units present a large variability in what concerns to dimensions and constitution. Mechanical properties of adobe are therefore characterized by a significant heterogeneity. For the experimental testing campaign, it was selected a set of samples representative of different existing adobe construction typologies, collected from eight houses and eight land dividing walls, from different locations. Samples were constituted, whenever possible, by entire adobe blocks, and a minimum of three samples by construction for each type of test was collected.

Cylindrical cores, with diameters ranging between 60 and 95mm, were extracted from the collected adobe samples units. These cylindrical cores had a height of approximately two times the diameter. A total of 101 cylindrical specimens, 51 proceeding from houses and 50 from land dividing walls, were submitted to mechanical tests. 83 specimens were submitted to compression, and 18 to splitting tests (Fig. 2).

The adobe specimens present significant compressive strength values, varying from 0.32 to 2.46MPa. For each construction analysed, the tensile strength corresponds to approximately 20% of the compressive strength. Results for the analysed adobe samples reveal a clear tendency for samples with larger fractions of small dimension particles to present superior compressive and tensile strength values.

The detailed description of the mechanical characterization testing campaign and of the obtained results can be found in Varum (2005) and in Varum, Costa and Pereira (2006).

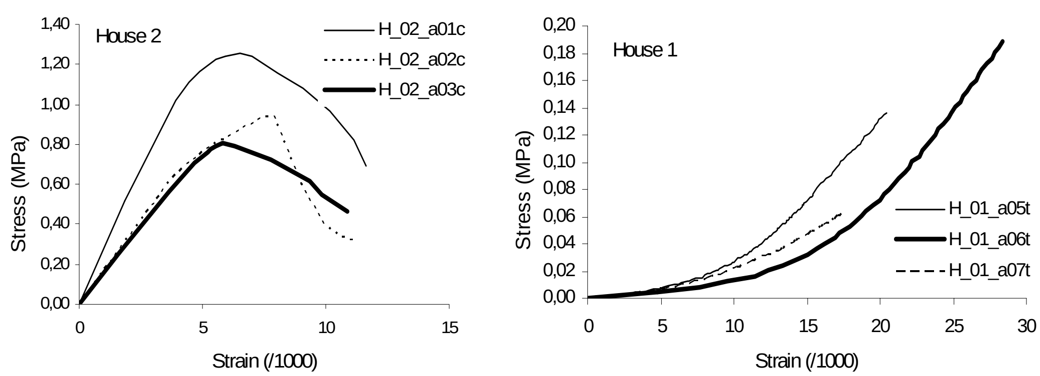


Figure 2. Stress vs strain relations obtained in simple compression and splitting tests.

2.3.2 Simple compression tests on mortar specimens

10 mortar samples (2 from plaster and 8 from joints) taken from 3 different houses were submitted to compression tests. The load applied by the compression testing machine was transmitted through two square steel plates, with 40mm side. It was obtained for the unconfined average strength: 1.68MPa (house 1); 1.07MPa (house 5); and, 0.45MPa (house 12).

2.4 Tests on full-scale adobe masonry walls

2.4.1 Introduction

It were conducted tests on adobe masonry wall specimens, one in laboratory and another *in situ* conditions, to characterize the mechanical behaviour and properties (stiffness, strength, energy dissipation capacity, common collapse mechanisms) of this masonry when subjected to horizontal cyclic actions, as those induced by earthquakes.

2.4.2 Laboratory tests

The wall tested in the laboratory was constructed with adobe units taken from an existing construction. These units have an average compressive strength of 0.85MPa and an average modulus of elasticity of 143MPa. For the joints it was adopted a mortar having a composition similar to the one traditionally used, with a compressive strength of 1.42MPa and a modulus of elasticity of 113MPa. The wall was constructed with the following dimensions: 1.08m height, 1.02m width and 0.185m thickness. The boundary conditions at the base of the wall avoid lateral displacements and rotations.

The wall tested in laboratory was subjected, initially, to a non-destructive dynamic test, to estimate the natural frequencies in each direction. These measured frequencies help on the dynamic characterization of the adobe masonry wall, and also on the calibration of numerical models. In a second phase, it was conducted a destructive test imposing constant vertical load combined with in-plane horizontal cyclic forces.

2.4.2.1 Dynamic test

The natural frequencies in the two horizontal directions (transversal and longitudinal) were measured with a seismograph.

The average modulus of elasticity of the wall can be estimated using Eq. 1:

$$\boldsymbol{\omega} = 1{,}875^2 \left(\mathbf{EI} / (\mathbf{ml}^4)\right)^{1/2} \tag{1}$$

where: $\boldsymbol{\omega}$ is the natural frequency [rad/s]; **E** is the average modulus of elasticity; **I** is the moment of inertia of the cross-section; **m** is the mass per unit length of the wall; and **l** is the total height. This expression is valid if it is assumed: i) cantilever dynamic behaviour for the wall; ii) constant cross-section; iii) uniformly distributed mass in height. An average modulus of elasticity of 316MPa was estimated using this expression and considering the measured transversal frequency (10.94Hz).

2.4.2.2 In-plane cyclic test

A constant vertical load of 2.86kN was applied on the top of the wall, to simulate the behaviour of a wall with double height, as commonly observed in existing constructions, and in-plane horizontal forces were imposed, in cycles of increasing amplitude, till the collapse was reached (Fig. 4). During the test, displacements were measured at four points on each side of the wall. In Fig. 3 is presented a general scheme of the testing layout, including the wall specimen and the loading and displacements measuring systems.

A maximum horizontal force of 3.2kN was applied. The failure mode was traduced by the opening of a horizontal crack at the base of the wall. This observed failure mode corresponds to the typical response of this type of masonry walls for low vertical stress levels. The reduced value of the vertical stress in the wall induces a rigid body behaviour, when subjected to horizontal cyclic loads, which is traduced by a rotation of the wall, almost intact, over its inferior and superior edges (“rocking”).

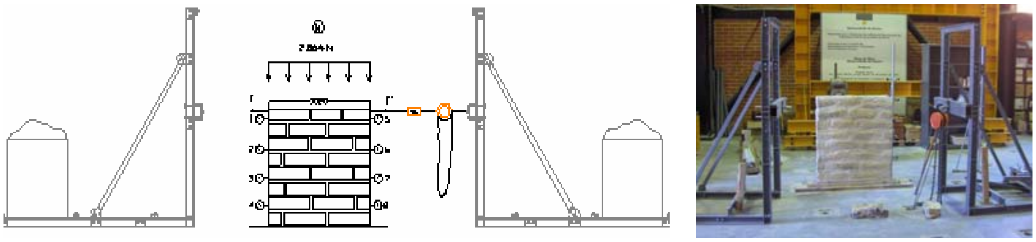


Figure 3. Laboratory testing layout: wall specimen; reaction frames; horizontal displacement transducers; dynamometer; and horizontal loading system.

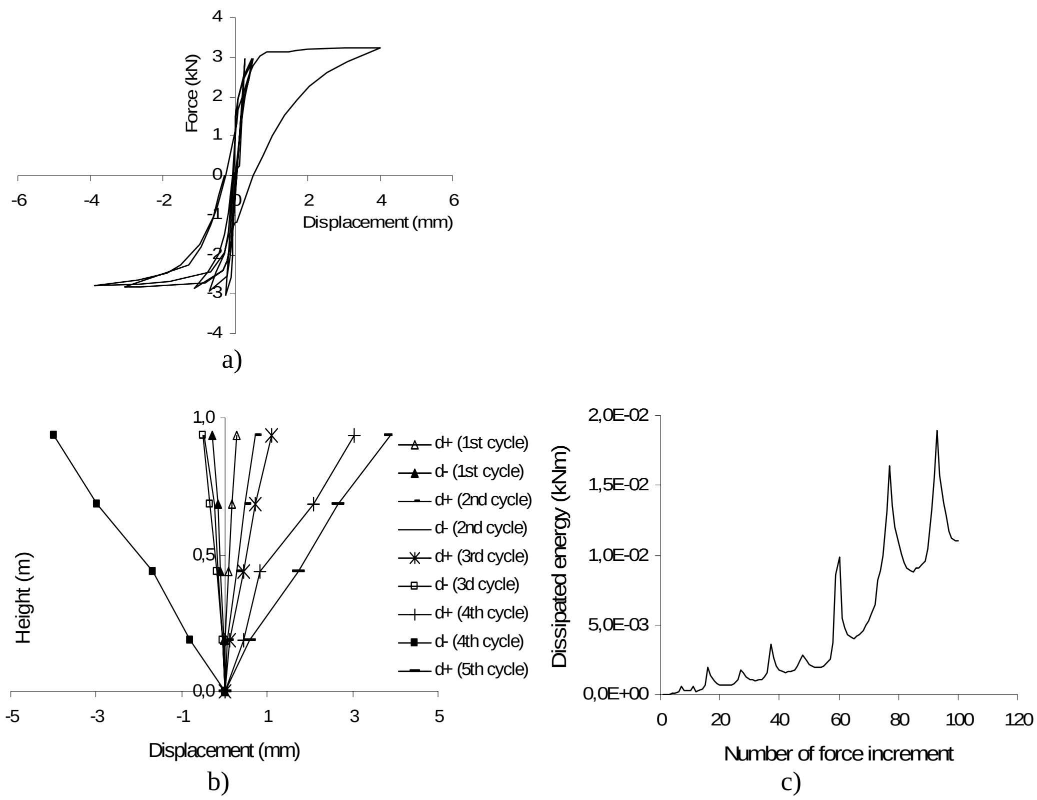


Figure 4. In-plane cyclic laboratory test results: a) applied horizontal force vs top-displacement; b) displacement profiles for peak horizontal forces; c) dissipated energy evolution.

2.4.3 *In situ* tests

The mechanical behaviour of an adobe masonry wall of a single storey building, *in-situ* conditions, with representation of the real material and support conditions, was studied. In *in-situ* tests, a more rigorous evaluation of the structural behaviour conditions of existing constructions, namely of the connections between perpendicular walls, the influence of roofing structural systems in the global response, as well as the influence of openings and other singularities, can be achieved.

The wall tested *in-situ* conditions had the following dimensions: 2.03m height, 3.73m width and 0.22m thickness. It presented a significant deterioration level, as can be observed in Fig. 5. This wall was subjected to dynamic characterization tests, and to two horizontal cyclic mechanical tests, namely: an in-plane semi-destructive test and an out-of-plane destructive test.

2.4.3.1 Dynamic test

Dynamic tests were conducted on the wall, to estimate its natural frequencies and modulus of elasticity. It was followed the same testing procedure described for the wall tested in laboratory. A frequency of 2.20Hz in the transversal direction was measured. With the measured natural frequency and using Eq. 1, an average modulus of elasticity of 101MPa was estimated.

2.4.3.2 Cyclic tests

2.4.3.2.1 In-plane cyclic test

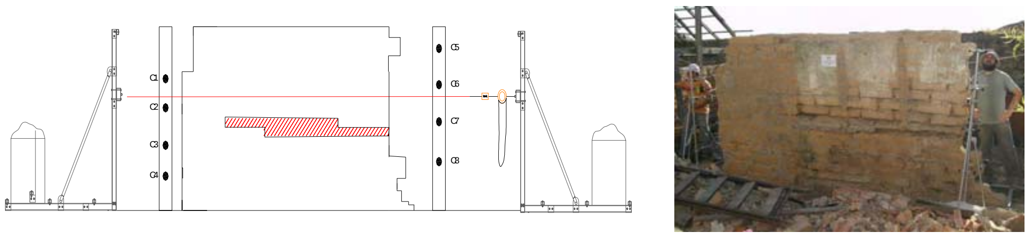


Figure 5. *In situ* in-plane testing layout: wall; reaction frames; horizontal displacement transducers; dynamometer; and horizontal loading system.

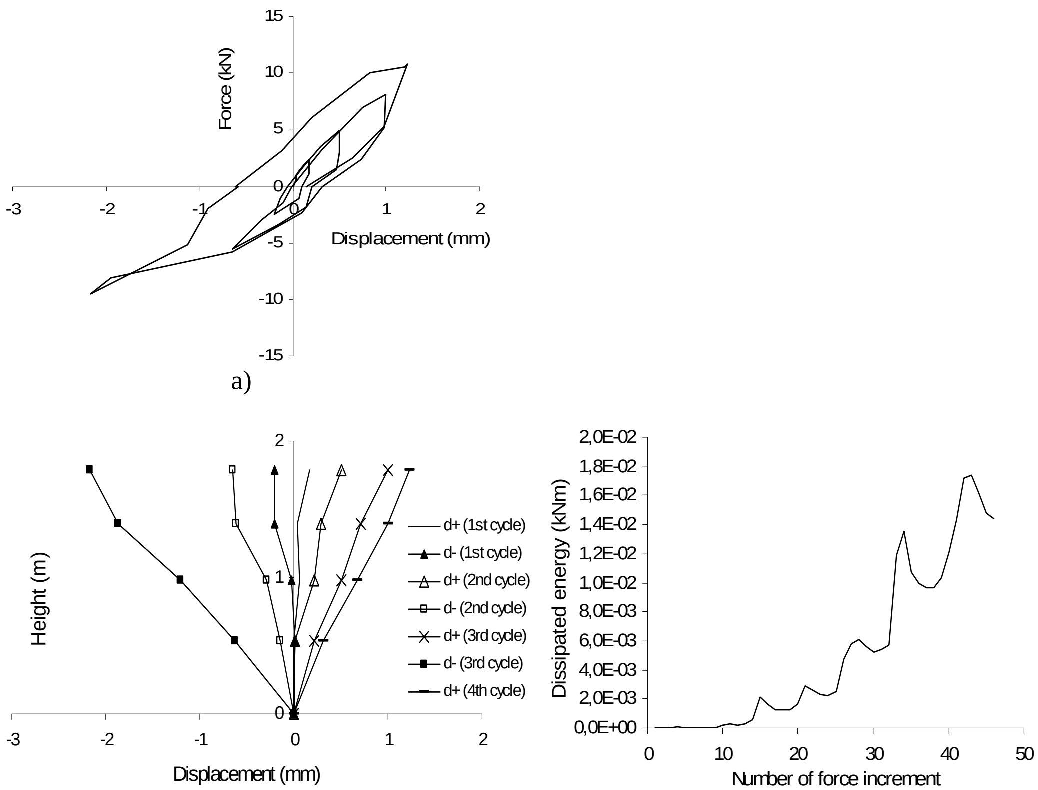


Figure 6. In-plane cyclic in-situ test results: a) applied horizontal force vs top-displacement; b) displacement profiles for peak horizontal forces; c) dissipated energy evolution.

For the cyclic tests it was not applied an additional vertical load. Initially, in-plane horizontal cyclic forces were imposed, in cycles of increasing amplitude (Fig. 6). In Fig. 5 is presented a general scheme of the testing layout, which is similar to the one adopted for the test in laboratory conditions.

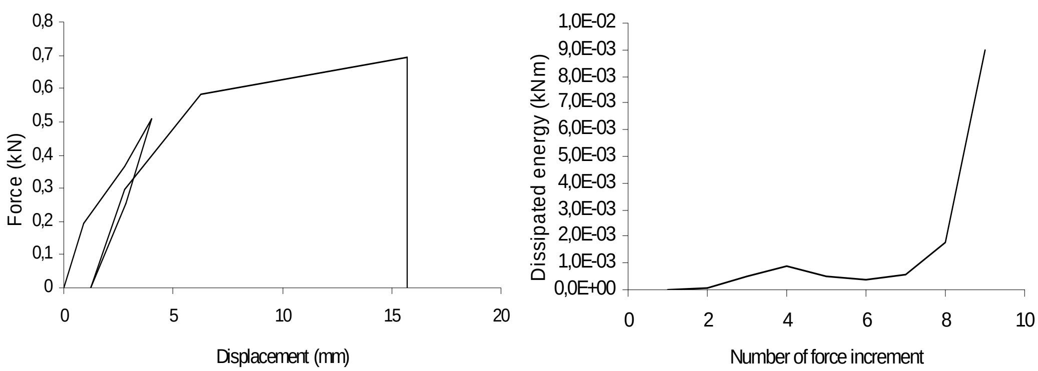
A maximum horizontal force of 10.7kN was applied. This force was not raised to a higher level in order to allow performing the out-of-plane test.

2.4.3.2.2 Out-of-plane cyclic test

In a second phase, adopting a different testing setup (Fig. 7), out-of-plane horizontal forces were applied to the wall, in cycles of increasing amplitude, but without inversion of the force signal, till the collapse was reached (Fig. 8).

A maximum horizontal force of 0.69kN was applied in the out-of-plane direction. The out-of-plane collapse happened for an imposed horizontal displacement of 16mm (approximately 0.95% drift). For the in-plane test similar drift values were imposed for forces 15 times superior without collapse. This, and the fact that the out-of-plane wall strength is less than 7% of the corresponding in-plane strength, demonstrate that this type of adobe wall elements are significantly more vulnerable to out-of-plane actions. The failure mode observed is characterized by a rotation at the base, with damage spreaded through the wall height.

Figure 7. *In situ* out-of-plane testing layout: wall; horizontal displacement transducers; and horizontal loading system.



a) b)

Figure 8. Out-of-plane cyclic in-situ test results: a) applied horizontal force vs top-displacement; b) dissipated energy evolution.

3 Conclusions and final considerations

The work presented in this paper is part of a project focused in the rehabilitation and strengthening of the adobe constructed park of Aveiro district. In this project, the following methodology is being followed: i) detailed survey of the existing constructions and of the commonest structural and non-structural pathologies; ii) material mechanical characterization; iii) structural characterization and evaluation of structural safety; iv) development of non-structural rehabilitation and structural strengthening solutions. Even though this research is focused in adobe constructions of Aveiro district, it may have repercussions in all regions of Portugal where earth construction appears with a significant expression (namely in Beira Litoral, Algarve and Alentejo), and also in other parts of the World with similar constructive systems.

The work developed and summarily presented in this paper, consists in the characterization of the mechanical behaviour and properties of adobe units and mortars, and in the investigation of the dynamic behaviour and structural non-linear response of adobe masonry walls when subjected to horizontal cyclic displacements. The principal obtained results are: i) strength and stiffness of adobe units and mortars; ii) strength, stiffness, energy dissipation capacity and common collapse mechanisms of adobe masonry walls. These results contribute for the enrichment of a basis of knowledge which can support the interpretation of observed structural pathologies, calibration of numerical models, structural safety assessment, and design of strengthening solutions adequate for existing adobe constructions, and even support the design and construction of new edifications.

4 Acknowledgments

The authors express their acknowledgments to Tiago Martins for his collaboration in the experimental work here summarily presented, to CIVILRIA, S.A. for the transport of adobe units to the laboratory, to MARTIFER, S.A. for offering the reaction steel frames used in the cyclic tests on adobe walls, and to all persons that kindly opened their own homes for samples collecting and testing on adobe constructions.

References

Hernandez, R. S., Barrios, M. S., and Pozas, J. M. M., 2000. Characterization of ancient construction materials (mud walls and adobe) in the Churches of Cisneros, Villada and Boada de Campos (Palencia), *Materiales de Construcción* 50(257), 33-45.

Oliveira, E. V., and Galhano, F., 1992. *Arquitectura tradicional portuguesa*, Publicações D. Quixote, Lisbon.

SAT, 1992. *Proc. of Seminário Arquitecturas de Terra*, CCRCentro, Portugal.

Varum, H., Martins, T., and Velosa, A., 2005. Caracterização do adobe em construções existentes na região de Aveiro, *IV SIACOT Seminário Ibero-Americano de Construção com terra and III Seminário Arquitectura de Terra em Portugal*, 233-235, ARGUMENTUM, Lisbon.

Varum, H., Costa, A., Pereira, H., and Almeida, J., 2006. Ensaios de caracterização do comportamento estrutural de construções existentes em adobe. *V SIACOT Seminário Ibero-Americano de Construção com terra and I Seminario Argentino de Arquitectura y Construccion con tierra*, 73-74, Eds. Mellace, R., Voltan, J., Cirvini, S. A., Viñuales, G. M., Neves, C. M., Rotondaro, R., and Montaña, E., Mendoza.

Varum, H., Costa, A., Velosa, A., Martins, T., Pereira, H., and Almeida, J., 2006. Caracterização mecânica e patológica das construções em Adobe no distrito de Aveiro como suporte em intervenções de reabilitação. *Houses and cities built with earth: conservation, significance and urban quality*, 41-45, ARGUMENTUM, Lisbon.